THE DESIGN, FABRICATION, AND TESTING OF COMPOSITE HEAT EXCHANGER COUPONS

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ABSTRACT

Several heat exchanger (HX) test panels were designed, fabricated and tested at the NASA Glenn Research Center to explore the fabrication and performance of several designs for composite heat exchangers. The development of these light weight, high efficiency air-liquid test panels was attempted using polymer composites and carbon foam materials. The fundamental goal of this effort was to demonstrate the feasibility of the composite HX for various space exploration and thermal management applications including Orion CEV and Altair. The specific objectives of this work were to select optimum materials, designs, and to optimize fabrication procedures. After fabrication, the individual design concept prototypes were tested to determine their thermal performance and to guide the future development of full-size engineering development units (EDU). The overall test results suggested that the panel bonded with pre-cured composite laminates to KFOAM Grade L1 scored above the other designs in terms of ease of manufacture and performance.

1. INTRODUCTION

Beginning with the first patent issued March 3, 1931, [1] the heat exchanger as we know it today has evolved to become a thermal tool used in a variety of situations. The first major uses of early graphite heat exchangers included industrial applications for heat dissipation of corrosive streams, including HCl and hydrogen peroxide flows [2]. Since then, carbon-foam technologies have evolved beyond their use as a material suited for applications requiring high strength and ultralow permeability.[2] Materials such as KFOAM have yielded thermal conductivity similar to aluminum at one-fifth the density along with a coefficient of thermal expansion that is close to silicon,[3] while the porous graphite grade POCO HTC developer states that it has two-thirds the thermal conductivity of copper at only one tenth the weight.[4] A combination of excellent thermal conductivity along with low density have made both materials prime candidates for use in modern heat exchangers.

A major concern of any space exploration program has been the management and reduction of the total system weight. This has often been accomplished through replacement of traditional components with those made of polymers, ceramics, or composites tailored to achieve desired strengths, weights, and other important properties. Eckel and Jaskowiak [5] have pointed out that high temperature composite heat exchangers offer the potential for mass reductions of greater than fifty percent over traditional metallic designs. They also offer the ability to operate at significantly higher operating temperatures facilitate operation at reduced coolant flows and make possible temporary uncooled operation in temperature regimes, such as experienced during

vehicle reentry, where traditional heat exchangers require coolant flow.[5] For this particular project, we explored the development of a light weight, high efficiency air-liquid (A/L) heat exchanger (HX) utilizing polymer composites paired with the aforementioned carbon foam materials. While the use of carbon foam materials in heat exchangers is not new, the development of a carbon foam heat exchanger enclosed in an autoclave processed polymer composite was not previously attempted.

2. MATERIALS AND DESIGN

2.1 Materials Used

- Carbon foams: several commercial foams were available for this HX application and two types were used for coupon fabrication. Their properties are summarized in Table I.

Table I. Various carbon foams available and their properties

Foam type ***Properties***	**POCO-HTC**	**POCO-Foam**	**KFOAM Grade D1**	**KFOAM Grade L1**	**GrafTech Developmental**
Density, g/cc	0.9	0.55	0.48	0.38	0.06 – 0.29
Porosity					
Total, %	61	75	72	70	70 - 89
Open (% of total)	95	96			
Average Pore Dia., μm	350	350	650	600	
Thermal Conductivity, Bulk					
Out-of-plane, W/mK	245	135	110	70	2.8 – 67.9
In-plane, W/mK	70	45			
Comp. Strength, MPa	5.895	2.99	363	2.50	.034 - .820
CTE, 50 -150°C, ppm					
Out-of-plane	-1.07	-0.7			
In-plane	1.02	0.6	0.69	3.0	

- Carbon fiber reinforced polymer matrix composite (PMC): three sets of composite prepregs were used, along with one woven fabric system. These are summarized below.
  - Composite Prepregs:
    (i) HFPE Polyimide/K1100 2k unidirectional carbon fiber, 304.8 mm wide, 63 g/m^2 FAW (Fiber Areal Weight), ~ 2.5 mm nominal thickness
    (ii) PMR-II-50 Polyimide/M60J 4HS woven fabric C-fiber with 6k tow, 215 g/m^2 FAW
    (iii) RS-9D Cyanate Ester/M55J 6k unidirectional carbon fiber , 304.8 mm wide, 69-70 g/m^2 FAW, 36% resin content, ~3 mm nominal thickness
  - IM7 carbon fiber 8HS woven fabric
- Adhesives/sealants: three major thermally conductive materials were chosen and are summarized below.
  - Duralco 133: two component, heat curing, Aluminum filled, thermally conductive (~5.8 W/mK) high temperature epoxy with viscosity of 36,500 cps after mixing
  - Hysol EA9394: two-part structural high temperature epoxy paste adhesive, aluminum filled, 160,000 cps viscosity after mixing for good gap filling and potting capabilities

with low toxicity
  - Tra-Bond 2113: clear, low viscosity (~300 cps after mixing) epoxy adhesive that contains no solvents with good flowability and wetting characteristics
- Metal tubes: All tubes were aluminum alloy 3003-H14 rated to 1.73-3.44 MPa, used in two different size configurations listed below.
  - 12.7 mm OD, 10.92 mm ID, 0.889 mm wall thickness for air inlet and outlet
  - 25.4 mm OD, 22.098 mm ID, 1.651 mm wall thickness for cooling fluid

2.2 Part Design

Typically, heat exchangers can be classified by 5 different identifying factors as defined by Kakaç and Liu: [6]

1. Recuperating or regenerating
2. Direct or indirect heat transfer process
3. Geometry used (tubes, plates, external surfaces)
4. Single phase or two phase heat transfer mechanics
5. Parallel, counter, or crossing flow arrangement

Using these terms, our system was designed as a recuperating, indirect tube/fin geometry utilizing a single phase heat transfer process in a counter-flow direction. The basic design shared by all of the prototypes consisted of two carbon foam blocks (152.4 mm x152.4 mm x25.4 mm) adhesively bonded together with Al tubes (one 25.4 mm diameter for cooling fluid in middle, passing through the entire block and two 12.7 mm diameter tubes for air inlet and outlet terminating just inside the composite surface) inserted between the blocks. Open-celled carbon foam, comprised of an interconnected network of thermally conductive graphitic ligaments, acted as the fin structure to cool hot air. The foam core was machined to maximize heat transfer between cooling tube and foam core by achieving intimate contact of foam ligaments with the tube surface.

A thermally conductive adhesive (e.g., Duralco 133) was also used to enhance heat transfer. Only a minimum amount of this adhesive was used (to reduce thermoconductive interference) with the majority filling in open cell cavities, and less on the ligaments. The two carbon foam blocks were only bonded along the edges (via a strip about 1.0 inch wide from the outer surface using the same thermally conductive adhesive). This enabled air to flow through the entire carbon foam core to maximize cooling exposure. The PMC casing provided structural integrity for the heat exchanger and also enabled air-tight sealing of the unit. The overall coupon design was developed for a modular HX structure, and was intended to demonstrate concept feasibility, i.e., it was not optimized for HX performance.

A total of seven coupon designs, designated D1, D2, D3, D4, D5a, D5b, and D6, were investigated. D1 and D2 were initial designs whose casing was constructed by adhesively bonding pre-cured composite laminates to the carbon foam core. These two designs differed in the type of foam core that was used, i.e., high density high thermal conductivity foam, POCO-HTC and low density foam, KFOAM Grade L1, respectively.

Some of the composite casings were constructed by wrapping composite prepreg tape over the foam core and curing the entire assembly together, hereafter referred to as the overwrap and co-cure options. The D6 coupon was fabricated by this option using POCO-HTC foam. POCO-HTC foam was selected as a baseline core material because of its high bulk thermal conductivity and high compressive strength. However, due to its high density and low porosity, a larger pressure drop on the air side was expected across the sample.

Panels D3 and D4 were designed to investigate the effects of the inclusion of air channels within the carbon foam on the pressure drop. The foam core and composite casing used for D3 and D4 were the same as for D6. The above cases are all shown in Figure 1.

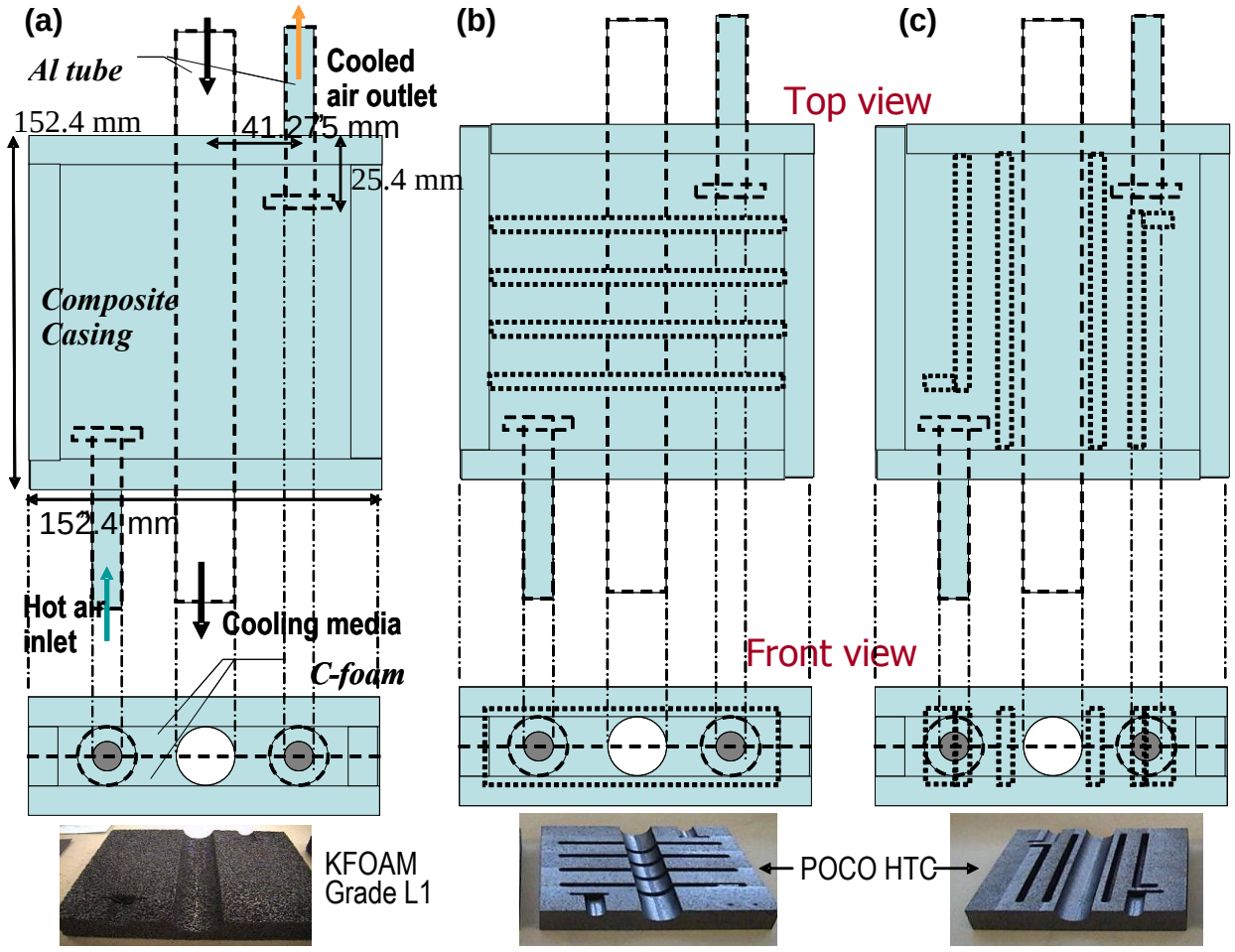

Figure 1. Schematic drawings of composite HX design and pictures of carbon foam used: (a) basic design (D1, D2) and (b), (c) designs with air channels in carbon foam core vertical or parallel to cooling tube (D3, D4, D6)

In the case of D5a and b, the composite casing was formed by carbon fiber preforming followed by vacuum assisted resin injection molding (VARIM), and co-curing. Two different carbon foams, POCO-HTC and KFOAM Grade L1, were used for D5a and D5b, respectively. Figure 2 shows the completed composite HX coupons representing each group.

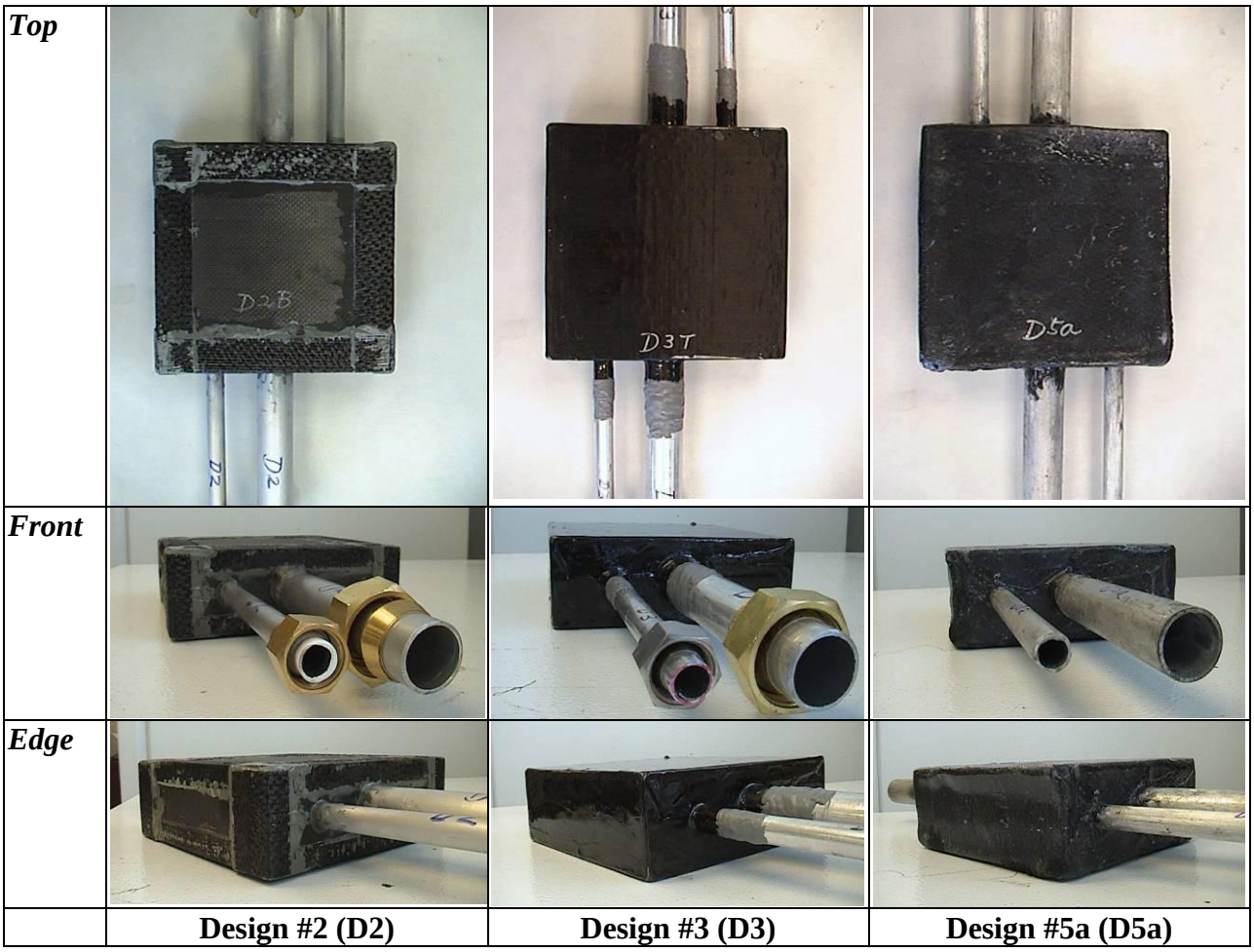

Figure 2. Representative composite HX coupons at various views, Design #2: Adhesively bonded composite; Design #3: Overwrapped composite; Design #5a: VARIMed composite

3. EXPERIMENTATION

3.1 Panel Fabrication

Before the addition of polymer matrix composite (PMC) facing to the heat exchangers, the carbon foams were first machined to proper dimensions according to their respective design type. Each foam was sanded with 500 grit sandpaper to soften the edges, remove abnormalities, and to ensure proper fit and bonding between the carbon foams and aluminum tubing. Connective areas of the aluminum tubing were also sanded, then cleaned with acetone and ethanol, and dried with a heat gun before bonding.

After cleaning, the carbon foams and aluminum tubing were "dry-fit" to ensure proper bonding would occur. For bonding, a thermally conductive adhesive (Duralco 133), was mixed first by hand then by Thinky mixer. A thin coat was applied evenly on the tubing and carbon foam to ensure proper adhesion between the two components. Two 25.4 mm thick carbon foams were bonded to each other using a 25.4 mm wide strip of adhesive on the outer edge; this was done to

enable air to flow through the entire carbon foam core to maximize cooling exposure. The tube and core assembly was clamped, weight applied, and was allowed to cure. Two approaches were then taken to cover the assembled core with a composite skin.

The first approach involved the fabrication of individual PMC composite panels for each face (front, back, and sides) and separate panels for the corners. The face panels were fabricated from HFPE polyimide composite prepregs, while the corners were PMR-II-50 polyimide composite prepregs. These panels were produced by a conventional vacuum-bagging and autoclave cure process, then machined to the desired dimensions. After machining, a treatment using scotch-brite pads and deionized water was used to clean the composite panels. They were then bonded to the carbon forms using Hysol EA9394 epoxy: the HFPE front, back, and sides first followed by the PMR-II-50 corner brackets. The coupon was then set to cure at appropriate conditions for the EA9394 epoxy in an air-circulating oven. The final product was then sanded and machined to remove excess epoxy.

The second approach used a complete over wrap process to cover the entire carbon foam. This was done in three dimensions (X-Y-Z), in order to provide a 6 ply panel covering over each side of the carbon foam. Before this could be accomplished, a layer of Hysol EA9394 was spread and cured onto all surfaces of the carbon foam to prevent the matrix resin from flowing into foam core during the curing process and to achieve air-tight sealing. RS-9D/M55J composite prepreg was chosen because of the ability of this material to be used on sharp edges without degradation during processing. This material was wrapped in an X-Y-Z fashion over the carbon foam using three different prepreg shapes. Appropriate use of pressure and heat gun drying helped the prepreg to stick to both itself and the carbon foam before processing. Small sections of the Al tubing were also coated for further reinforcement. Once the wrapping process was complete, the entire assembly was vacuum bagged and autoclave cured according to the conditions required by the composite material.

3.2 NDE

Before HX testing occurred, the bonding integrity of each composite casing was examined by two NDE (non-destructive evaluation) techniques: Infra-red (IR) thermography and Laser Shearography (after each cure and post-cure cycle for all designs, and before and after assembling the corner brackets for D1 and D2 panels.) It is important to note that D5a and b panels were not tested due to excessive leaking.
Typical NDE results are shown in Figure 3.

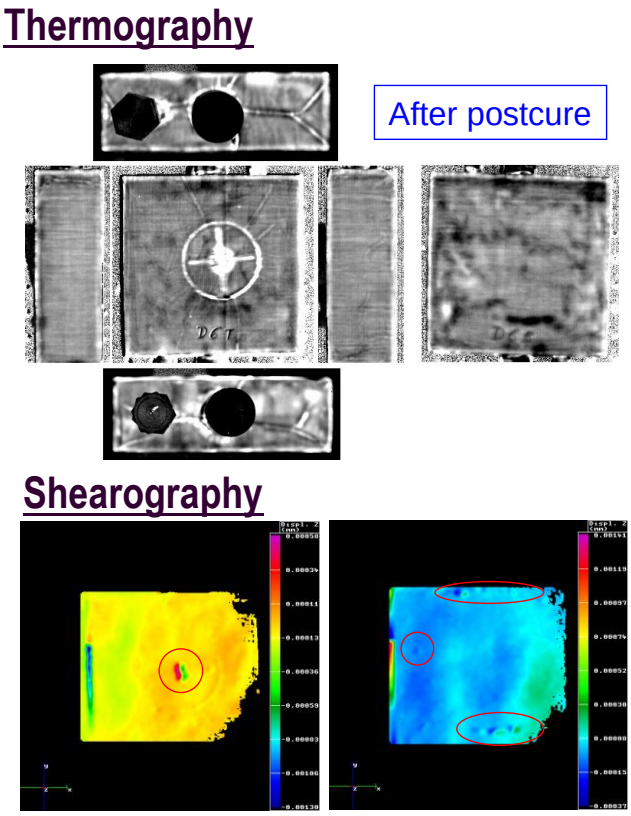

Figure 3. Typical NDE results via Thermography and Shearography of Design #6 coupon

Dark areas in the thermography indicate a slower cooling rate which can be caused by poor bonding, delamination, or resin rich areas, e.g., thicker epoxy sealing on C-foam surface. In most test panel cases, no changes were observed before and after postcure, i.e., no thermal stress-induced damage on the composites or bonding. Shearography after post-cure showed indications (disturbance in the displacement field) at scattered locations marked with circles, this was mostly due to the presence of resin poor or rich areas as indicated by the IR-thermography.

All completed composite HX test panels were then tested for leaks by applying compressed air at about .035 - .138 MPa internal pressure and monitoring with a commercial leak test compound solution. Despite the fact that the previous NDE results indicated that the composite casing was well bonded to the C-foam core, most coupons initially failed the leak tests, mostly due to small pin holes at the edges or corners or at the Al tube-composite interfaces. In the case of D3, D4, and D6 in which the core was wrapped and co-cured with unidirectional composite prepreg, leaking was also observed from the flat surfaces.

Composite HX test panels, with the exception of D5a and b, were then re-sealed externally using either low viscosity Tra-Bond 2113 epoxy for most flat surfaces and interfaces or Hysol EA 9394 epoxy paste for edges, corners, and Al tube-composite interfaces. Subsequent testing showed that all re-sealed coupons passed the leak testing, allowing the overall HX performance testing to be performed.

3.3 Testing

The HX testing apparatus used in the evaluation of the heat exchanger coupons was required to supply air at approximately 29.4°C and cold liquid at approximately 4.44 °C, while monitoring the input and output temperatures and pressures of the hot and cold fluids. In these experiments, the hot air supply originated in building-supplied instrument air at .861 psig. The air pressure was reduced using a filter-regulator and heated using a heating element wrapped around a length of 25.4 mm diameter stainless steel tube. Temperature control was provided using a PID controller. The temperature input to the PID controller was obtained from a dedicated thermocouple placed in the center of the output air stream. This control scheme regulated the temperature at the outlet of the heater rather than at the inlet of the coupon, reducing the chance of overdriving the heater in response to leaks or losses at the coupon. Losses between those two points had to be compensated for by manually increasing the set-point of the heater while monitoring the inlet temperature at the coupon. The losses were constant as very little adjustment was necessary once the target coupon inlet temperature was reached. The airflow was measured using a 0 – 30 SLM mass flow meter. The cold fluid was a 50:50 mixture of deionized water and Dowfrost HD, a commercial propylene-glycol – based heat transfer fluid. The fluid was chilled using a recirculating chiller equipped with a bypass valve. Since the chiller produced a flow rate higher than required even with the bypass valve fully opened, a needle valve was placed in the water loop. The pressure and temperature changes across the coupon for each fluid were measured using 0 – .35 MPa pressure transducers and type T thermocouples. The pressure transducers were placed on the inlet and outlet tubing immediately adjacent to the coupon; the thermocouples were adjacent to the pressure transducers. In this way, pressure and temperature changes in the tubing connecting the components of the system were minimized. A fifth thermocouple was attached to the body of the heat exchanger, but it was moved after the initial test runs to the cold water outlet tube directly adjacent to the composite body of the heat exchanger.

1. RESULTS

Testing showed a significant difference in the temperature of the inlet and outlet air, but essentially no difference in the inlet and outlet temperatures of the water. A calculation of the Reynolds Number for the cold water flow in the tube under test flow conditions indicated laminar flow in the tube and, therefore, the possibility of a radial temperature gradient in the cold water tube. When the thermocouple monitoring the outlet water temperature was centered in the tube, it measured a temperature unchanged from the inlet temperature. Relocation of the body thermocouple to the surface of the cold water outlet tube showed a significant temperature rise. In the laminar flow conditions present in the cold water tube, only the fluid in the immediate vicinity of the tube wall was warmed.

Seven composite HX test panels were fabricated to test the effect of core and face-sheet materials, core design and processing methods on panel performance. The overall assessment of each of these designs in terms of their performance and manufacturability is summarized in Table II. Through qualitative analysis, it was found that designs D1 and D2 were the optimal choice; they showed good structural integrity along with the best manufacturability and air sealing when compared to the other designs. Despite having no additional foam air channels

(which made processing easier), these coupons showed the highest change in air temperature (with values of -17.5 °C and -18.4 °C respectively) along with coupon D2 having the lowest pressure change of all tested coupons (-0.00048 MPa). Despite coupons D3, D4 and D6 having the best structural integrity, they did not perform as well as the initial coupons, with temperature changes of -16.9°C and -16.8°C along with pressure changes of -0.0158 MPa and -0.0283 MPa. The additional processing time and effort for over wrapping composite, along with the creation of channels in the foam gave D3 and D4 lower qualitative scores for processing difficulty than coupons D1 and D2. Both VA-RIM coupons (D5a and D5b) performed poorly in all tests, and were unable to give any reliable numbers for air sealing, along with temperature and pressure drops. The additional machinery and time needed for the VA-RIM process itself made these the most difficult coupons to process.

Design ***Factors***	**D1**	**D2**	**D3**	**D4**	**D5a**	**D5b**	**D6**
Core	HTC	Grade L1	HTC	HTC	HTC	Grade L1	HTC
Air channels	none	none	vertical	parallel	none	none	none
Composite casing	pre-cured	pre-cured	prepreg	prepreg	preform	preform	prepreg
Fabric type	uni-fabric for faces, 4HS woven for brackets		uni-fabric	uni-fabric	8HS woven	8HS woven	uni-fabric
Corner/Seam	brackets	brackets	overwrap	overwrap	overwrap	overwrap	overwrap
# of ply	6 for face 4 for bracket		6	6	2	2	6
Matrix Resin	polyimide	polyimide	cynate ester	cynate ester	epoxy	epoxy	cynate ester
Bonding	adhesive	adhesive	co-cure, vac bagging	co-cure, vac bagging	VA-RIM	VA-RIM	co-cure, vac bagging
Weight- total, gm	1324	715	1160	1146	1308	903	1251
Core	~ 930	~ 317	863	846	~ 930	~ 320	~ 940
Al tubes	188	188	188	188	~ 188	~ 188	188
PMC f/s	~ 100	~ 100	50	51			~ 60
Adhesive+Sealant	~ 106	~ 110	58	61			~ 60
Material cost, $	~1100	~500	~1000	~1000	~950	~400	~1000
Process							
Equipment Needs	oven, autoclave	oven, autoclave	oven, autoclave	oven, autoclave	RIM, autoclave	RIM, autoclave	oven, autoclave
difficulties	low	low	medium	medium	high	high	medium
Structural Integrity	good	good	better	better	poor	poor	better
Manufacturability	better	better	good	good	poor	poor	good
Air Sealing	better	better	good	good	poor	poor	good
Performance							
ΔT_{air}, °C	-17.5	-18.4	-16.9	-16.8	n/a	n/a	-15.8
ΔP_{air}, MPa	-.0875	-0.00048	-.0158	-.0283	n/a	n/a	-.0717

Table II. Summary of composite HX design-process-manufacturability-performance relations

2. CONCLUSIONS

Favorable factors, properties and performance for the composite A/L HX test panels are highlighted in yellow in Table II. From this comparison, it is clear that the D2 panel scored above the other designs in terms of ease of manufacture and performance. Key findings from these panel fabrication trials included (i) the lower density and higher porosity carbon foam performed better than the higher density and higher bulk thermal conductivity (TC) foam, i.e., HX performance was controlled more by the local ligament TC than the bulk TC of the carbon foam; it was also lighter and cheaper, (ii) air channels considerably lowered pressure drops, especially vertical channels, and (iii) the pressure drop results were consistent with reported data for the POCO-HTC foam core (~.0005 MPa/mm).

3. REFERENCES

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